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TITLE *CORONAL HEATING BY NANOFLARES: PLASMA DYNAMICS OF ELEMENTARY EVENTS*

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Coronal Heating by Nanoflares: Plasma Dynamics of Elementary Events

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Abstract. It has been suggested by Parker (1983, 1988), Sturrock *et al.* (1990), and others that the corona may be stochastically heated, on spatial scales at or below current instrumental resolution limits, by a continuous succession of many small flare-like events commonly referred to as *nanoflares*. In this paper we extend a semi-analytical "point" model developed previously for solar compact flares (Kopp and Poletto, 1990), to include gravitational plasma downfall during the late decay phase. Applying the model to conditions representative of nanoflares allows us to predict the temporal variation of average plasma properties in such events and should ultimately facilitate a calculation of the spectral characteristics of a nanoflare-heated corona.

1. Introduction

During the past few years the plethora of coronal heating theories has been augmented by still another candidate - namely, heating via a sporadic sequence of tiny impulsive energy releases in the coronal plasma. These elementary impulsive outbursts, which lie at or below the resolution limits of existing telescopes, have become known as *nanoflares* (Porter *et al.*, 1987; Parker, 1988). The energies of individual nanoflares range from $< 10^{24}$ to $\sim 10^{27}$ erg. It should be pointed out that the idea of nanoflare heating of the corona does not necessarily comprise a fundamentally new dissipation mechanism. Rather, it represents an attempt to identify precisely the coronal sites where an already known mechanism, for example magnetic reconnection on small scales, is at work, and to associate these sites with observable features on the Sun.

The present work is aimed at understanding the plasma dynamics on the coronal loop where a nanoflare (NF) occurs. To this end, and in view of the fact that current instruments are incapable of resolving the spatial structure of these events, it seems reasonable to adopt a theoretical description cast in terms of spatial averages of the thermodynamic variables. When instruments with the required resolution ($\lesssim 10^2$ km) become available, more complete hydrodynamical modeling will undoubtedly be called for.

2. Description of the model

We consider a rigid magnetic loop with ends rooted deep in the chromosphere, of semi length $L \ll$ the pressure scale height. Prior to the NF, the loop pressure is equal to that of the upper chromosphere and the temperature is that of the background corona. (The subsequent time behavior of the loop plasma, however, is quite insensitive to these preflare conditions.)

The sudden release of energy identified with the nanoflare instantaneously raises the loop temperature without immediately changing its density. The elevated temperature causes enhanced downward thermal conduction, which in turn leads to evaporative filling of the loop from the chromosphere. This process continues until the back-pressure of the loop plasma becomes sufficient to impede further evaporation, whence the filling stops and the plasma radiatively cools and at the same time begins to fall back into the chromosphere.

A simple model to describe this scenario - including thermal conduction, chromospheric evaporation, and optically thin radiative losses (but neglecting gravitational downfall) - has been developed by Kopp and P[illegible]tto (1990) in the context of solar and stellar compact flares. These authors actually treated the case of a non-rigid flux tube, which was free to expand laterally to maintain pressure equilibrium with the surrounding corona. Thus, the present problem represents the "low-β limit" of the more general case. Integrating the energy and continuity equations over the loop semi-length, L, and assuming the pressure to be spatially uniform at each instant, yields two total differential equations for the average loop density, $\rho(t)$, and pressure, $P(t)$:

$$\frac{d\rho}{dt} = \frac{\rho v}{L},$$

$$\frac{dP}{dt} = \frac{\gamma P v}{L} + \frac{\gamma - 1}{L}[(F_c - F_{c0}) + (F_r - F_{r0})],$$

where γ is the specific heat ratio; F_c, F_r, and F_{c0}, F_{r0} are the conductive and radiative fluxes at times t and $t = 0$ (pre-flare atmosphere), respectively; and

$$v = \frac{\gamma - 1}{\gamma} \cdot \frac{F_c - F_{c0}}{P} \equiv v_{evap}$$

is the evaporation velocity. The temperature is given in terms of $P(t)$ and $\rho(t)$ by the ideal gas equation of state.

An approximate treatment of the effect of gravity on the solutions may be gained by replacing the above expression for v by $v = v_{evap} - v_d$, where $v_d = (1 - \rho_0/\rho)v_{ff}$ is the gravitational downflow speed; here v_{ff} is the free-fall speed from the loop summit. (The *ad hoc* multiplier $(1 - \rho_0/\rho)$ on v_{ff} ensures that the downflow will vanish when the loop density has returned to its preflare value, ρ_0.) Now, early in the event $v_{evap} \gg v_{ff}$; thus the presence of gravity will become noticeable only after conductive cooling has lowered the loop temperature somewhat and the strong evaporative upflows have begun to subside.

Numerical integration of these equations, starting from the enhanced values of T and P produced by the nanoflare heating, yields the plasma history following the impulsive phase. For the original application to compact flares, comparison of the model (without gravity) with a detailed hydrodynamical simulation by Pallavicini *et al.* ([illegible]83) showed qualitative agreement over much of the flare decay phase; the inclusion of gravitational downfall in the manner indicated above substantially improves this comparison, particularly at late times.

3. Calculations and discussion

Nanoflares are the visible manifestations of sudden energy releases on discrete magnetic flux tubes threading the low corona. As was mentioned previously, they occur over a broad range of energies and sizes. As a specific example we now consider the response of an average coronal loop (semi length $L = 10{,}000$ km) to a typical NF energy release ($E_t = 10^{25}$ ergs), which we assume occurs instantaneously at $t = 0^+$. Parker (1988) estimates the diameter of an elementary coronal flux rope to be of order 200 km; this, in conjunction with the above numbers, gives an average volumetric energy release of $\epsilon_t \sim 16$ erg cm^{-3} over the total length ($2L$) of the loop.

Figure 1 depicts the run of loop temperature and plasma velocity as functions of time after the NF onset. The high initial temperature ($\sim 10^8$ K) is an artifact of the simple model and will probably not be realized in practice, since the actual energy release will be spread over some brief but finite time interval. Note that the temperature falls rapidly at first, decreasing to values of less than 10^7 K in about 50 s. This behavior is consistent with the observed soft X ray

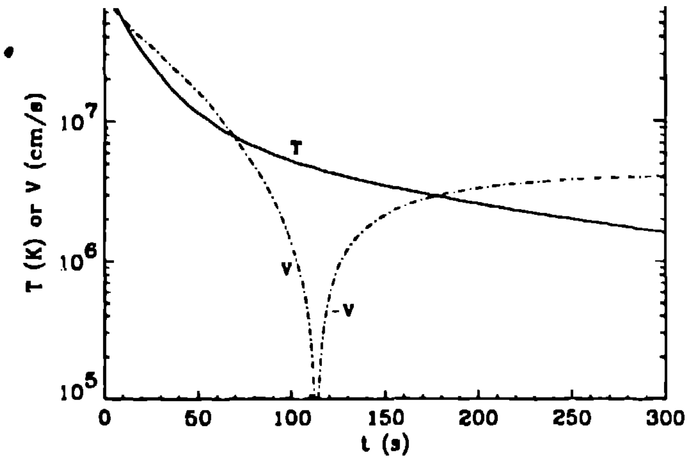

Figure 1. Time history of loop temperature and plasma velocity for the "typical" nanoflare described in text.

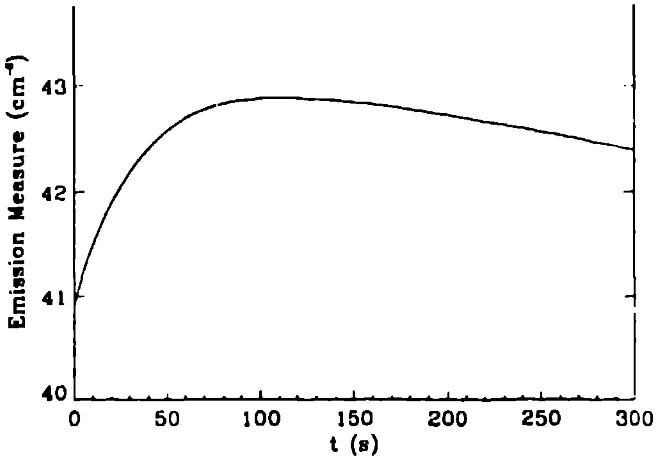

Figure 2. Nanoflare emission measure versus time.

lifetimes of nanoflares in the range 20 to 60 s (Porter *et al.*, 1987). At later times the decline of temperature becomes much more gradual, as the evaporated plasma cools and settles back into the chromosphere. At very late times (not shown in the figure) the loop plasma asymptotically returns to its preflare state, which we have taken to be that of a static background corona with $T_0 = 10^6$ K and $P_0 = 0.1$ dyne cm^{-2}.

Figure 2 shows the temporal variation of emission measure (EM) for our NF model. Since the loop volume remains invariant, the EM reflects first the increase in electron density caused by strong chromospheric evaporation, and subsequently the slow return to preflare conditions as the evaporated plasma cools and settles back into the chromosphere. With current instruments one cannot expect to measure accurately the peak EM ($\sim 10^{43}$ cm^{-3}) of an individual nanoflare. However, to supply the average 10^7 erg cm^{-2} s^{-1} required to heat the corona (Withbroe and Noyes, 1977), implies that approximately 3×10^6 such events are in progress at any time. The composite EM from 3×10^6 of our model nanoflares, namely 3×10^{49} cm^{-3}, is roughly the same as the observed X-ray emission measure of the entire corona.

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